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Membrane photobioreactors for integrated microalgae cultivation and nutrient remediation of membrane bioreactors effluent

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Abstract: The feasibility of a new concept of wastewater treatment by combining a membrane bioreactor (MBR) and a microalgae membrane photobioreactor (MPBR) is assessed in this study. In this system, the organic carbon present in wastewater is expected to be fully oxidized in the MBR, while the nutrients are removed via the subsequent MPBR treatment. The effluent of a lab-scale MBR was fed into a PBR and a MPBR which served as growing medium for *Chlorella vulgaris*. The MPBRs demonstrated their superiority by limiting the algae wash-out, thus increasing the allowable optimum dilution rate (D_{opt}). At these corresponding D_{opt} values, 3.5 and 2 times higher biomass concentrations and volumetric productivities respectively were achieved by the MPBR. It is also possible to run the MPBR at still higher biomass concentration, thus enabling a smaller footprint and higher nutrient removal efficiency. However, reduced nutrient removal efficiencies were found to be one possible drawback.

Keywords: membrane photobioreactor, microalgae, nutrient recovery, effluent treatment

1. INTRODUCTION

Water scarcity and increasing demands for high quality water urge the advancement of wastewater treatment (WWT) technologies. Two of the established and mature technologies on WWT for both municipal and industrial wastewater are the activated sludge process (ASP) and (more recently) the membrane bioreactors (MBRs). The installed number of MBRs is growing significantly due to their advantages compared to the ASP, particularly the excellent and consistent effluent quality, the smaller footprint and the possibility to decouple hydraulic (HRT) and sludge retention time(SRT),thus allowing lower sludge production (Judd, 2010).

In a WWT process, nutrient removal(mostly nitrogen (N) and phosphorous (P)) is necessary before releasing the effluent to the environment to avoid nutrient enrichment or eutrophication which imbalance the ecosystem (Aslan and Kapdan, 2006; Pittman et al., 2011). To remove N and P, the ASP and MBR can be tuned to allow for biological nutrient removal (BNR) through the combination of various anaerobic, anoxic, and aerobic tanks (Monclús et al., 2010; Sun et al., 2010). Besides using microbiology, a chemical precipitation process may also be used to remove P. The aforementioned methods are energy-intensive and involve extra equipment instruments, which may cover 60-80% of the total energy consumption in the treatment process especially when dealing with large amounts of N and P(Maurer et al., 2003; Michael et al., 2008). In addition, the increasingly strict rules on wastewater discharge require very low nutrient concentrations in the discharge flows. There is thus a clear demand for a cheap and efficient process to remove more N and P at a lower cost.

Integration of microalgal cultivation in a wastewater treatment process is one alternative to remove nutrients. Different types of wastewater have been extensively studied as microalgal growth medium, including municipal, agricultural, industrial, and synthetic wastewaters (Pittman et al., 2011). The use of wastewater as a medium and nutrient source to grow microalgae would also act as an environmentally sustainable solution to fulfill the needs for freshwater and nutrient supplementation to microalgae cultivation. Essential nutrients, mainly N and P, must be present in order to fulfill the algae growth demand (Chisti, 2007; Richmond, 2008). Even though the cost of fertilizers (N and P) was found to cover only 14.8% of the total material cost in algae cultivation (Acién et al., 2012),integrating microalgae in wastewater treatment would still be very useful and would become even more important when considering the fast depletion of P-sources and environmental sustainability.

Research on wastewater for microalgae cultivation has been done in various manners: batch-wise, semi-continuous and continuous (Dickinson et al., 2013; Ruiz-Marin et al., 2010; Ruiz-Martinez et al., 2012). In a batch cultivation of *Chlorella vulgaris* using a synthetic wastewater as feed, it was found that nutrient removal was very effective for N and P at corresponding concentrations below 22 and 7.7mgL^{-1} (molar ratio of N/P of 6.32)(Ruiz-Martinez et al., 2012). *Scenedesmus sp.* in continuous mode completely removed N and P from the municipal wastewater with respective concentration of 20-21 mgL^{-1}and 2.4-3.0 mgL^{-1} (N/P of14.7-19.3). A biomass productivity of 0.3 g L day^{-1} at dilution rates of 0.7 to 1.05 day^{-1} was achieved (Harun et al., 2010). Thus, it is proven that such wastewaters are ideal growth media for various types of microalgae.

It is worth noting that microalgae are photo-autotrophic, and thus cannot use organic carbon present in wastewater as carbon source. Consequently, no removal of such substances can be realized when solely using microalgae to treat wastewater. Therefore, in the common practice where abundant organic carbon is present in wastewater, an appropriate approach would be to remove the carbon first via a simplified ASP or MBR and then to polish the effluent using microalgae in a PBR.

Different types of closed PBRs exist, such as vertical column, flat panel, and tubular PBRs. In a continuous mode, biomass concentration and productivity depend strongly on the dilution rate, due to occurrence of algae wash-out. For instance, Tang et al.(2012) increased the dilution rate of a continuous PBR up to 10 times and found that the biomass concentration decreased from 0.726 to 0.061 g dry weight L^{-1}. Due to this wash-out problem, ordinary PBRs will only be limited to use the D_{opt} to achieve maximum productivity and nutrient removals. Consequently, a very large PBR volume is required, since only very low D_{opt} values are applicable.

One way to face the aforementioned problem is by applying membranes, which allow to decouple the dilution rate (related to HRT) and (bio)mass retention time (MRT). This way, higher biomass concentrations and productivities may be obtained (Bilad et al., 2013; Honda et al., 2012). The decoupling of HRT and MRT is also important considering the relatively low N and P concentrations in domestic wastewater. For example, microalgae cultivation using wastewater effluent with a typical N concentration of 15-20 mg L^{-1} will only support microalgae growth concentration to about 0.2 g L^{-1}, which is very low (Peccia et al., 2013). Without membranes, the attained biomass concentrations can be too low to be considered for recovery, as this would finally result in a very high harvesting cost.

With regards to wastewater nutrient remediation from MBRs by microalgae, recent work screened four different species of microalgae batch-wise, followed by continuous MPBR for 23 day using a 10-L flat panel photoreactor (Singh and Thomas, 2012). The study proved that microalgae were able to remove (completely or partly) NH_4, NO_3, NO_2, and PO_4^{3-}. However, this study was focused only on the nutrient removal point of view without evaluating the system productivity at single dilution rate.

In the current study, further advancements on the MPBR performances are evaluated. A PBR and an MPBR were used to polish a lab-scale MBR effluent (fed with simulated domestic wastewater and operated without anoxic treatment process) as the medium. The performance of the PBR and the MPBR was first simulated. Both systems were then run to treat MBR permeate at variable dilution rates. The performance of the two systems was evaluated by their ability to remove nutrients and their productivity. Finally, the practical implication and the sustainability analysis are also discussed.

2. METHODS

2.1. Microalgae and growth medium

The microalgae grown in this study was *Chlorella vulgaris* (SAG, Germany, 211-11B). They were cultivated initially batch-wise(data not included) until reaching the stationary growth state in Wright's cryptophytes (WC) medium (supplementary material). The pH and temperature of the broth were measured daily and were in the range of 8-9 and 15-22°C respectively. After 10 days of batch cultivation, the feed was switched to MBR permeate for the continuous experiments. A lab-scale MBR was used to treat a synthetic wastewater made from cat food (Perfect Fit Pro) which perfectly simulated the properties of domestic wastewater. The MBR permeate was used as microalgae feed, containing nutrients; i.e. N and P which were fluctuated during the experiment in the range of 7.48 to 22.1 $mgL^{-1}$and 1.69-2.17 mgL^{-1}, respectively. The details of feed composition and a number of parameter on the MBR operation are provided in the supplementary material.

2.2. PBR and MPBR operations

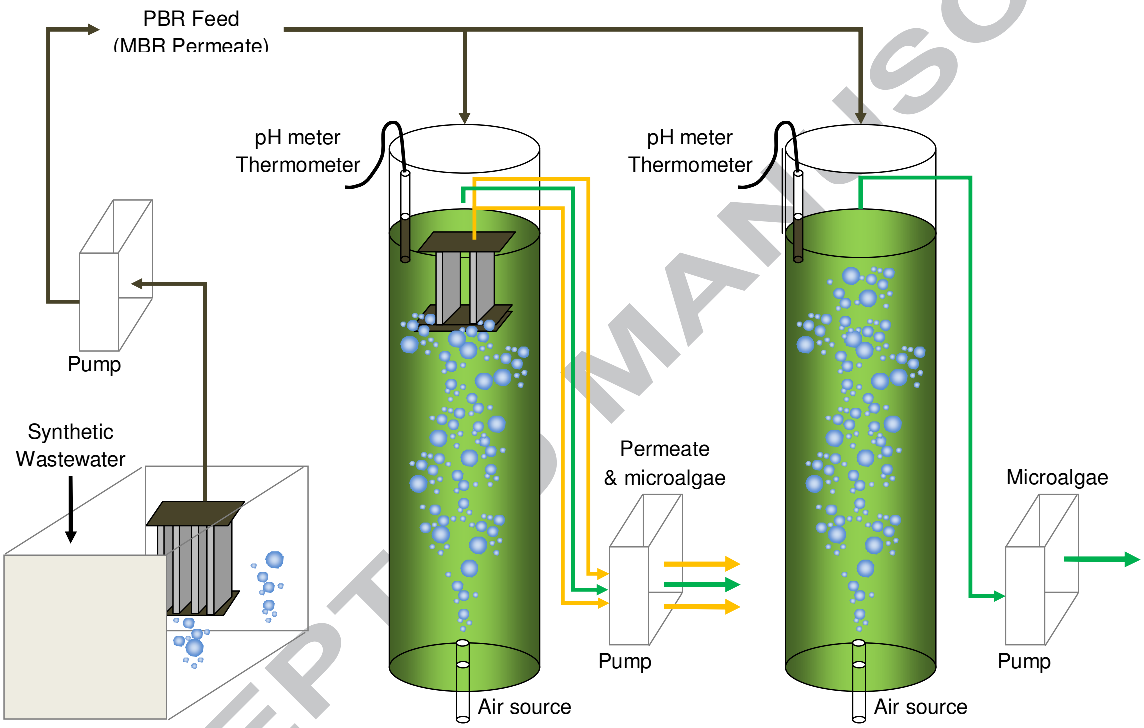


Figure 1 The schematic illustration of the combined aerobic MBR and microalgae cultivation using MPBR and PBR. PBRs consist of bubble columns equipped with an air bubble source at the bottom of the reactors, peristaltic pumps to suck the permeates, and pH and temperature sensors.

Figure 1 shows the schemes of the MPBR (left) and the PBR (right). Each bioreactor had a working volume of 25 L. The feed and outflow of the PBRs were pumped at the same rate using a multi-channel peristaltic pump (Watson-Marlow 205U, UK). In the MPBR, the outflow consists of a number of channels consisting of permeate lines from the membrane and of retentate lines. All PBRs were equipped with pressurized air sources (5 L day^{-1}) for CO_2 supply, mixing and membrane fouling control. The reactors were illuminated by two fluorescence lamps (2x36 W, Sylvania, Germany) placed close-by the reactor. The two systems were operated without dark phase. In addition, since the PBRs were positioned quite near a window, variable light input from outside was unavoidable. During the experiments, around 500 mL demineralized water was added every day to both reactors to make up the evaporated water (~4% v/v).

Two cultivation experiments were done using one conventional PBR (i.e. without membrane) and one MPBR. The MPBR used 4 sheets of 0.016 m^2 chlorinated polyethylene (PE) membranes (Kubota, Japan), operated at a volumetric reduction factor (υ) of 5. This υ-value is defined as the ratio of feed flowrate to retentate (product) flowrate. The MPBR was able to fully retain the biomass.

Four dilution rates (D) were used for the two cultivations, starting from the lowest D of 0.20 day^{-1}, followed by higher D's of 0.30, 0.40, and 0.50 day^{-1}. Two additional D's, 0.7 and 1 day^{-1}, were applied to the MPBR. These D's resulted in the corresponding fluxes which were in the range of 2.6 to 13 Lm^{-2}h^{-1}. In order to obtain representative data, at least 1.5 x HRT was used as the time for each dilution rate to give a total of six months continuous operation. However, the filtration performance (i.e. membrane fouling) is out of the scope of this study and will not be discussed in detail. Previous studies in our group have been dedicated to these aspects of similar microalgae filtrations (Bilad et al., 2014, 2012).

2.3. Growth simulation in PBR and MPBR

A basic simulation of microalgal growth in the PBR and MPBR was carried out in order to project their performances. The growth rate kinetics were approached by the Monod equations and the continuous cultivation was simulated as in an ideal chemostat (Shuler and Kargi, 2002). This approach was also used in our previous study (Bilad et al., 2014). The derivations of the growth kinetics are provided in the supplementary material. Table 1 shows a number of important parameters of the PBRs.

Table 1 Parameters used in growth simulation in PBR and MPBR*

Parameter	PBR	MPBR	
Dilution rate (D, day^{-1})	$D = \frac{F_{in}}{V}$		(1)
Hydraulic retention time (HRT, day)	$HRT = 1/D$		(2)
Volumetric reduction factor (υ)	-	$\upsilon = \frac{F_{in}}{F_{retentate}}$	(9)

Biomass retention time (MRT, day)	$MRT = HRT$	(3)	$MRT = \upsilon.HRT$	(10)
Growth rate (μ, day^{-1})	$\mu = D$	(4)	$\mu = \frac{D}{\upsilon}$	(11)
Substrate concentration in the reactor (S, gL^{-1})	$S_{PBR} = \frac{D \cdot K_s}{\mu_{max} - D}$	(5)	$S_{PBR} = \frac{D \cdot K_s}{\mu_{max} - D} \cdot \upsilon$	(12)
Biomass concentration in the PBRs (X, gL^{-1})	$X_{CPBR} = Y_{X/S}\left(S_{feed} - \frac{D \cdot K_s}{\mu_{max} - D}\right)$	(6)	$X_{CPBR} = Y_{X/S}\left(S_{feed} - \frac{D \cdot K_s}{\upsilon\mu_{max} - D}\right) \cdot \upsilon$	(13)
Biomass productivity (P, gL^{-1}day^{-1})	$\mathrm{P} = X_{CPBR} \cdot D$	(7)	$\mathrm{P} = X_{MPBR} \cdot \frac{D}{\upsilon}$	(14)
Substrate or nutrient removal efficiency (η, %)	$\eta = \frac{S_{feed} - S_{PBR}}{S_{feed}} \cdot 100\%$	(8)	$\eta = \frac{S_{feed} - S_{MPBR}}{S_{feed}} \cdot 100\%$	(15)

*F_{in} is flowrate (L day^{-1}), V reactor volume (L), $Y_{X/S}$ yield of biomass to limiting substrate (g g^{-1}), S concentration of limiting substrate (g L^{-1}), Ks saturation constant (g L^{-1}), and μ_{max} maximum growth rate (day^{-1})

2.4. Sampling and analytical methods

50mL daily samplings were taken from the PBRs for analysis. Microalgal dry weight as total solids was measured gravimetrically according to a standard method (American Public Health Association et al., 1992). Nitrogen and phosphorous concentrations in the feed and in the PBRs were measured in clear supernatant by using Hach-Lange standard kits (Merck, Darmstadt, Germany). The visual appearance of microalgae was gradually monitored using light microscopy.

3. RESULTS AND DISCUSSION

3.1. Growth model, nutrient removal and reactor volume simulation

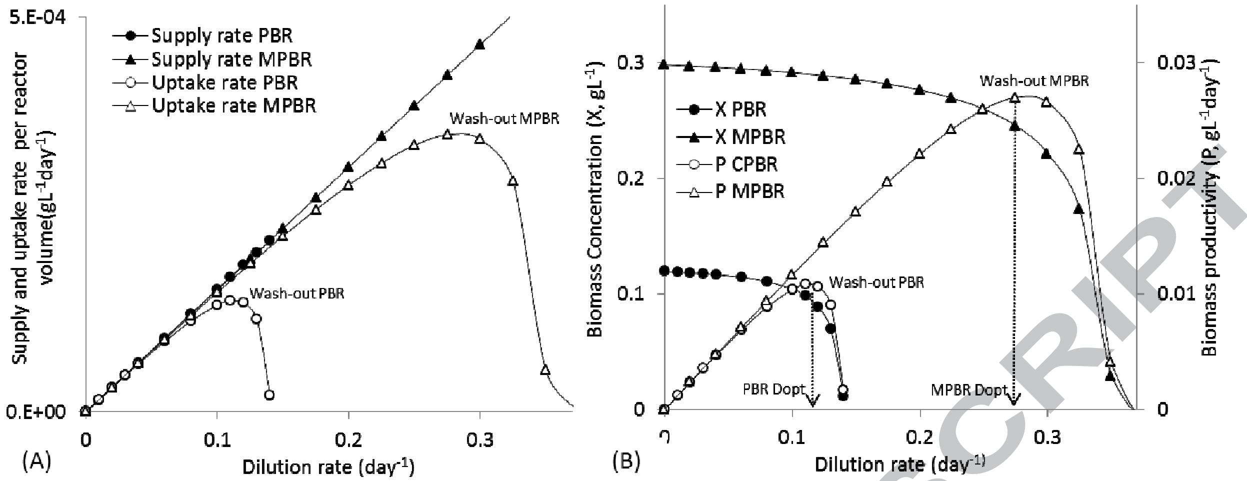


Figure 2 The simulation results showing (A) the supply and uptake rate of limiting substrate and (B) the biomass concentration and biomass productivity in a model of PBR and MPBR (with a υ of 2.5). The D_{opt} is the optimum dilution rate where each system achieves maximum productivity. Beyond D_{opt}, wash-out occurs. The simulation was performed using μ_{max}, K_S, S_o and Yx/s of , 0.15 d^{-1}, 0.1 mg L^{-1}, 1.55 mg L^{-1} and 77 g g^{-1}, respectively.

Figure 2A and B show the simulation of limiting substrate supply and uptake rate per reactor volume, biomass concentration and productivity for both PBR and MPBR. Figure 2A shows the supply and uptake rate of substrate in the PBRs which increases linearly with D until one value of D (Dopt) where the uptake rate starts to decline. Operating beyond D_{opt} will also decrease the biomass concentration and productivity (Figure 2B). This reveals the advantages of coupling a membrane with a PBR: allowing operation at higher D and avoiding wash-out problems. It allows the MPBR to operate at higher D, thus enables higher substrate uptake rates and results in higher biomass concentration and productivity. In the PBR, only low D's can be applied due to the wash-out problem. It thus requires a larger reactor volume and footprint to treat a specific volume of feed compared to the MPBR.

In the simulation (Figure 2B), the D_{opt} of the PBR is around 0.1 day^{-1} giving its maximum productivity of 0.01 $gL^{-1}day^{-1}$. On the other hand, higher D's can be used in the MPBR in order to obtain a higher productivity. The D_{opt} value of the MPBR is around 0.27 day^{-1} with the maximum productivity of 0.027 $gL^{-1}day^{-1}$. These increased values are related to the volumetric reduction factor (υ), which is also equivalent with the biomass concentration factor (in the case of complete biomass retention). Applying a certain value of υ allows a pre-concentration step of the algal suspension before further harvesting. This may thus reduce the costs in the later concentration and dewatering process.

From a biomass productivity point of view, which also relates to the substrate uptake rate (Figure 2A and B), the PBRs don't differ when using a low D (below D_{opt} of PBR). This is because at small D, a substantial assimilation time is available for both systems to achieve maximum uptake. At higher dilution rate, the MPBR shows its superiority by maintaining a high concentration of algal suspension due to the biomass retention by the membrane (decoupling between HRT and SRT), thus resulting in higher productivity and nutrient removal efficiency compared to an ordinary PBR.

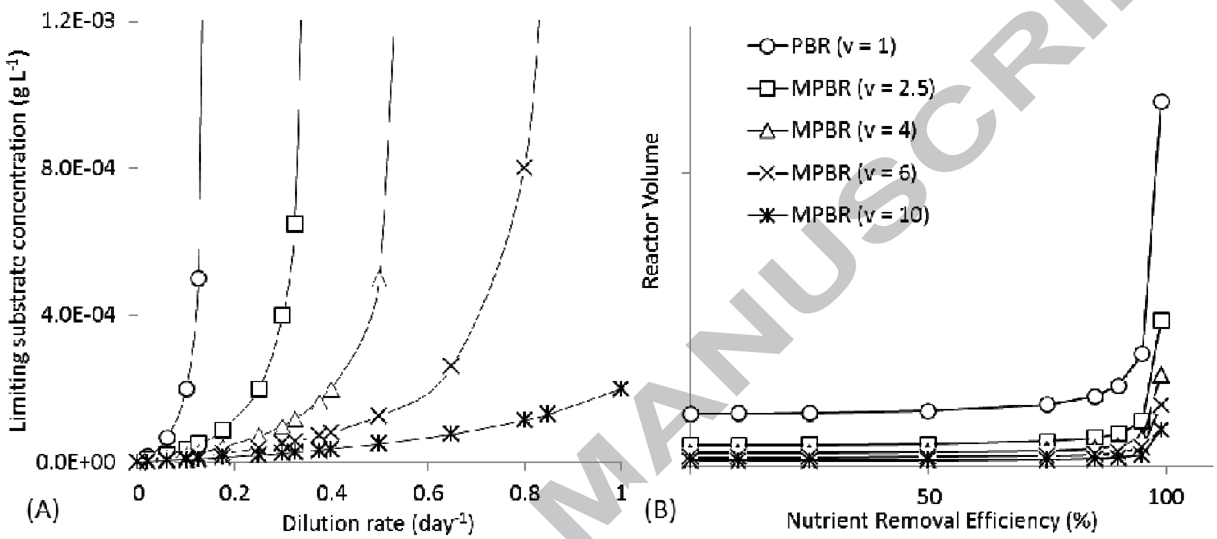


Figure 3 The simulation results for the PBR and the MPBR (with different values of υ) showing (A) limiting substrate concentration and (B) required reactor volume with its corresponding nutrient removal efficiency. Applying MPBRs with higher υ results in higher biomass concentration, thus allowing better uptake of the nutrient/limiting substrate and smaller reactor volume.

For nutrient removal in wastewater treatment, one of the main consequences of operating at higher D is a higher nutrient concentration in the effluent due to a shorter assimilation time (Figure 3A), thus giving a lower nutrient removal efficiency. However, it can be anticipated with increasing υ. Figure 4A clearly shows that by applying a higher υ, which enables the operation at higher algae concentration, the lower substrate concentration in the MPBR can be lower, thus giving higher nutrient removal efficiency. At such conditions, more efforts would be required to sustain the membrane permeance over an extended operation. A recent study showed an increasing membrane fouling tendency when the feed has a higher biomass concentration (Bilad et al., 2012).

In relation to the applied D, υ, and the obtained nutrient removal, a certain reactor volume is needed, as can be seen in Figure 4B. It reveals the advantage of applying a membrane in a PBR, which is to enable a smaller reactor volume. This fact becomes more important if a very high nutrient removal (>95%) is demanded. Without membranes, nutrient removal in wastewater treatment using microalgae will surely require a larger space.

3.2. Continuous PBR and MPBRs performances

3.2.1. Biomass concentration: wash-out behavior

The profile of the biomass concentration in the PBRs as a function of D is shown in Figure 4. It is worth noting that slight variations are present on each data point which may be due to the experimental conditions (sunlight and temperature) which sometimes changed. Figure 4 clearly shows the occurrence of wash-out in the PBR, even at the beginning of the experiment (D: 0.2 day^{-1}), which is indicated by a continuous decrease of the biomass concentration with increasing D. As a consequence, the PBR only allows operation with a D value below 0.2 day^{-1} to obtain its optimum concentration (at ±0.17 g L^{-1}).This concentration is very low, which requires a 100-400 times volumetric reduction during primary algae harvesting to reach the required final algae concentrations of 2-7% w/w (Uduman et al., 2010).

In contrast to the PBR, the MPBR was (to some extent) able to prevent wash-out by keeping the biomass concentration relatively higher in a wider range of dilution rates. The optimum biomass concentration of 0.59±0.1g L^{-1} was achieved by the MPBR at a D of 0.5 day^{-1}. By comparing the performances of the PBR and MPBR at their D_{opt}, a 3.5-fold biomass concentration was obtained by MPBR. This result significantly reduces the load of the harvesting step. For the primary harvesting step, the PBR output will need a 400^x volumetric concentration factor (by assuming 100% harvesting efficiency) to concentrate 0.17 g L^{-1} microalgal suspension to a 70 g L^{-1} concentration,which corresponds to 7% microalgal slurry. On the other hand, the MPBR only requires a120^x volumetric concentration factor (Uduman et al., 2010). Applying membranes in the MPBR thus enables to reduce significantly the energy consumption in the harvesting process.

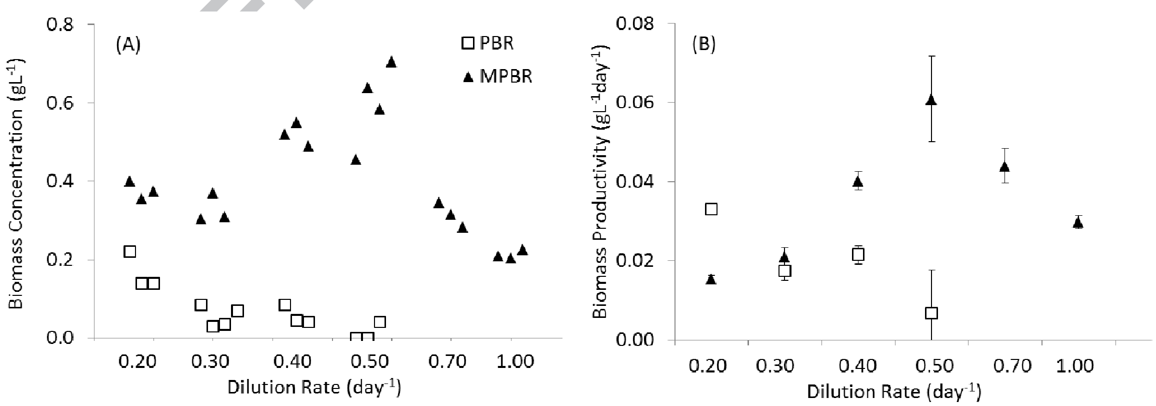


Figure 4 Biomass concentration (A) and productivity (B) for the two PBRs at different dilution rates. Wash-out occurred in the PBR, indicated by the continuous decrease of the biomass concentration. MPBR was able to prevent wash-out until D: 0.5 day^{-1}, allowing a higher biomass concentration and productivity.

3.2.2. Biomass Productivity

Figure 4B clearly shows how the biomass volumetric productivity may vary depending on the D of the PBRs. The MPBR reveals its superiority compared to the PBR, especially when operating at D ≥ 0.3 day^{-1}. While the PBR obtained its maximum productivity of 0.033±0.009 g L^{-1} day^{-1}at D of 0.2 day^{-1} (HRT: 5 days), the MPBR succeeded to produce 0.06±0.01g L^{-1} day^{-1}at much shorter HRT (HRT of 2 days, corresponding to D of 0.5 day^{-1}).

In a continuous reactor, the applied D (related to HRT) to treat a specified volume of wastewater determines the volume of the reactor. Higher D and lower HRT mean that a smaller reactor volume is needed. Thus, in the case of an MPBR, the prevention of wash-out which allows the reactor to operate in a higher D surely becomes one significant advantage compared to the PBR. Smaller reactors can be used in MPBRs, which is also indicated in the higher value of the biomass volumetric productivity that can be achieved.

3.3. Nutrient removal

Figure 5A to D show the relation between the nutrient supply, uptake, and the corresponding nutrient removal efficiencies in the PBR and MPBR. Figure 5C and D present the supply and uptake rate of N and P (per reactor volume) which refer to the rate of N and P provided from the MBR effluent and consumed by the microalgae, respectively. The composition of the MBR effluent fluctuated during the cultivations. However, this fluctuation somehow can represent the real situation of domestic wastewater.

Regarding the N and P concentration as well as the N/P molar ratio, their values fluctuated during the experiment. However, microalgae were still able to be cultivated. The concentrations of P were relatively stable for all runs in the range of 1.69 to 2.17 mg/L (corresponding supply rate in Figure 5D). In contrast to the P, the N concentrations varied more, ranging from 7.48 to 22.1 mg/L (corresponding supply rate in Figure 5C). When running the PBR, the molar N/P ratio was in the range of 9.7 to 12.9, while for the MPBR, slightly higher and wider N/P ratios were observed in the range of 15.5 to 22.8. These ratios are slightly higher compared to the N/P ratio of the microalgae biochemical composition (N/P = 11) which was thought to be the optimal condition for freshwater microalgae (Richmond, 2008), including *Chlorella vulgaris*.

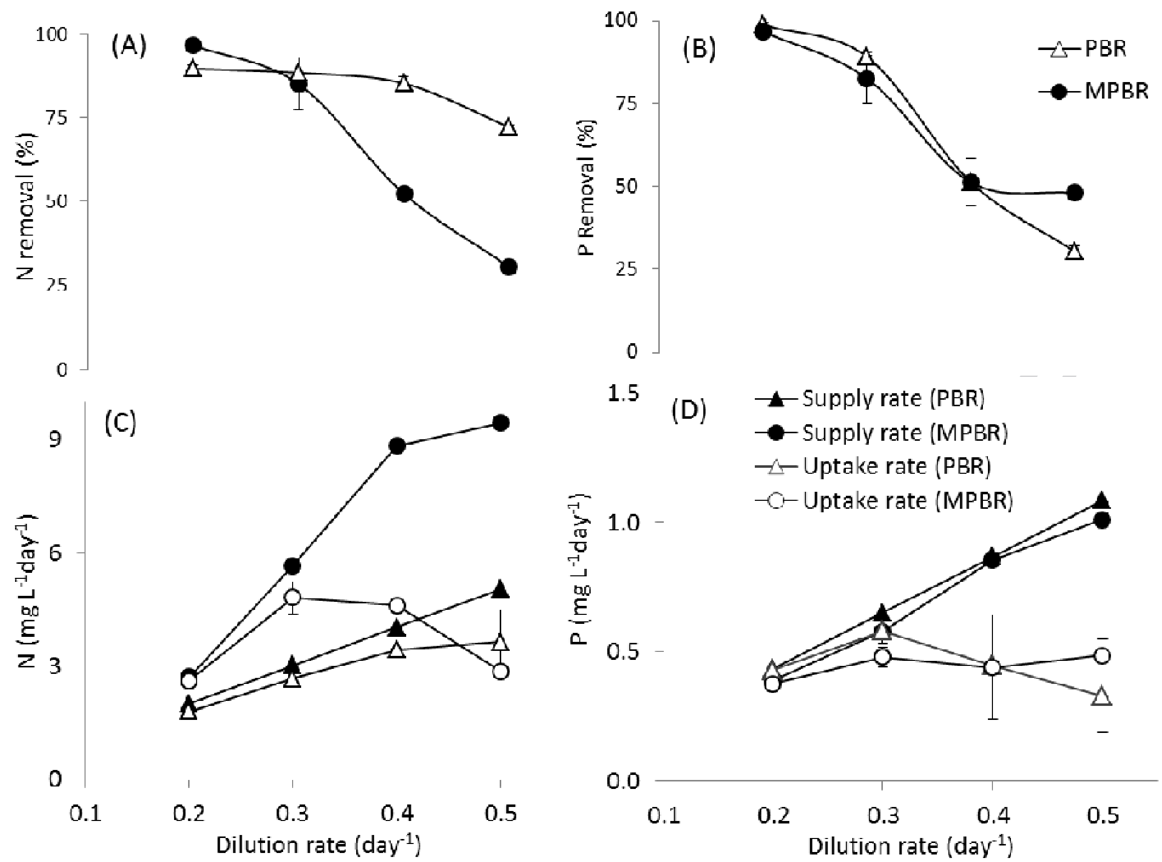


Figure 5 Nitrogen (A) and phosphorous (B) removal efficiencies of the PBR and MPBR, and their corresponding supply and uptake rates (C and D) as a function of dilution rate.

Increasing D in the PBRs are followed by an increase of N and P supply rate (mg L^{-1} day^{-1}). However, the uptake rate of the nutrient by the microalgae in both systems was not proportional to the increase of the supply. It tends to increase initially and stabilize at a certain point (the point when D_{opt} is reached). This phenomenon is acceptable, since, at higher D, the contact time between biomass and nutrients is lower. Apart from that, beyond D_{opt}, the biomass concentration also decreases. In addition, variations on several aspects may occur during the experiments, such as: light limitation, light/dark cycle, N/P ratio of the feed, and also the algae species (Aslan and Kapdan, 2006) which further influences the uptake rate and removal efficiencies. As higher dilution rates are applied in MPBR, the microalgal biomass concentration increased. Hence, light limitation due to the high density of microalgal may occur, or the inorganic carbon availability might became the limiting substrate since the air flowrate was kept constant at ~5L min^{-1}. The latter might be more probable, since the reactor pH was not controlled and often reached ~9 (i.e., it ranged from 8-9).

Figure 5A and B show the nutrient removal efficiencies of the PBR and MPBR which decreased with increasing D. High nutrient removal (>80%) for both N and P could be achieved by the PBR and MPBR at low dilution rate (D: 0.2 and 0.3 day^{-1}). In contrast to that, at higher dilution rate (D: 0.4 and 0.5 day^{-1}), the P removal efficiency of the MPBR dropped to 50%. For the PBR, an even lower P removal efficiency below 30% was observed for D 0.5 day^{-1}.These P removal efficiencies indicate the wash-out from the PBR which results in lower biomass concentration and thus lower uptake. The conclusion of correlating the P concentration with the wash-out is also relevant, since from our previous study it was shown that P is the limiting substrate for the growth (Bilad et al., 2014). For N removal, the MPBR has lower removal efficiencies compared to the PBR due to the higher concentration of N in the feed, as mentioned previously.

The value of the aforementioned removal efficiency corresponds to the wide-ranging N and P concentration in the effluent, i.e. 0.5 to 13 mgN L^{-1} and 0.18 to 1.08 mgP L^{-1} respectively. Using high D's may give benefit due to the high microalgal productivity, but the incomplete nutrient removal becomes a drawback in which high concentrations of N and P exist in the wastewater. The lowest removal efficiency of MPBR at a D of 0.5 day^{-1} gave the maximum N and P concentration. Thus, it is important to still choose the optimum dilution rate in order to compromise between biomass concentration and productivity on the one hand and the nutrient removal on the other. Depending on the maximum threshold value for disposal, the N and P content may be either tolerable or not. As a reference, the European discharge limit is 15 mg N L^{-1} and 2 mg P L^{-1} (European legislation (91/271/CEE)). Based on this reference, the N and P value obtained by MPBR at D of 0.5 day^{-1} are still acceptable.

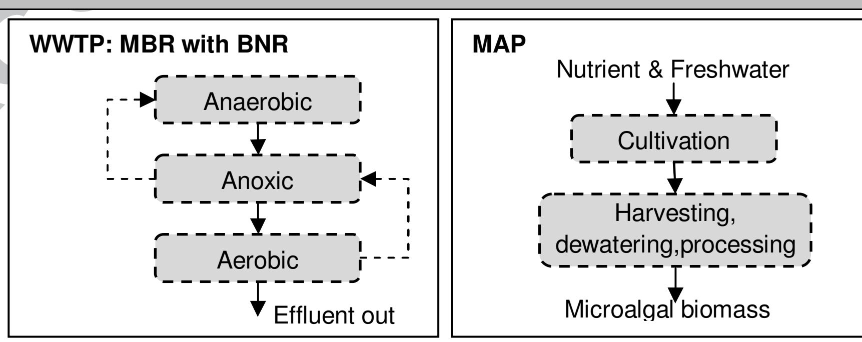
3.4. Practical implications

Bubble column PBR, the type of the PBR used in this experiment, is known to be one of the most practical closed PBRs, due to its compactness, good mixing and low energy consumption (Brennan and Owende, 2010).However, it has also a number of limitations, one of them is the small illumination area. The PBRs applied here provide an illumination area of $0.5m^2$, thus giving a surface to volume ratio of $20m^2/m^3$. This value is far below the optimal surface ratios (80-100 m^2/m^3) and consequently may result in a high dark fraction inside the reactors (Posten, 2009). Nevertheless, a good mixing, provided by the air bubbles might haveminimized the effect of this occurrence.

In order to estimate the areal productivity of an outdoor plant of the current PBR type, a simplified approach as in Chini Zittelli et al.(2006) was done. The distance between the reactors is estimated to be proportional to the size (diameter and length) taking into account the shadowing effect. In the current experiment, a column with 20 cm diameter was used for 25 L of biomass suspension. Based on this size, an area of 0.3 m^2 is estimated to be required per PBR. Thus when applying their optimum D's, an areal PBR of 2.76 g m^{-2} day^{-1} at a D-value of 0.2 day^{-1} (HRT: 5 days) could be realized, while the MPBR would reach 5.08 g m^{-2} day^{-1} at a higher D-value of 0.5 day^{-1} (HRT: 2 days). These numbers indicate the effectiveness of MPBRs in increasing the productivity and reducing the footprint for algae production. Nevertheless, since this calculation neglected the difference in sunlight due the location and also configuration of the reactors, the values of the areal productivity may increase or decrease depending on the real required ground area.

In addition to the advantages of MPBRs discussed earlier, they also improve the scale-up feasibility. Since the location of most municipal WWT plants is close to or inside a city, finding sufficient space can be a challenge, especially for plants with huge capacity(Lundquist et al., 2010). Therefore, MPBRs which require less space are more feasible to be applied. Regarding the light supply which is also crucial for microalgae processing, it is worth to mention that since the membranes are situated centrally in the reactor, they do not interfere with the light supply to the microalgae in the reactor. Membrane fouling is also somehow minimized by the air scouring, which is simultaneously used for mixing the reactor and for supplying CO_2.

Results suggest that even when coupled with a membrane, nutrient uptake rates are still strongly controlled by D. However, the MPBR also has another parameter that can be exploited, namely the volumetric concentration factor (υ), as explained in Figure 3A and B. Applying a higher υ will force the system to work at a very high biomass concentration, thus increasing the uptake rate and removal efficiency. However, under this condition, membrane fouling will probably be more severe because the membranes are exposed to high biomass concentrations. Nevertheless, this approach will be very effective to achieve high biomass productivity and nutrient removal which are important parameters for microalgae production and wastewater treatment respectively. A detailed study on the effect of υ will be addressed in a further study.

<table>
<tr><th>Case</th><th>Schematic</th><th>Remarks</th></tr>
<tr><td>A</td><td>
</td><td>Disadvantages:
• WWTP: High energy and cost of BNR
• MAP: Cost of nutrient and freshwater</td></tr>
</table>

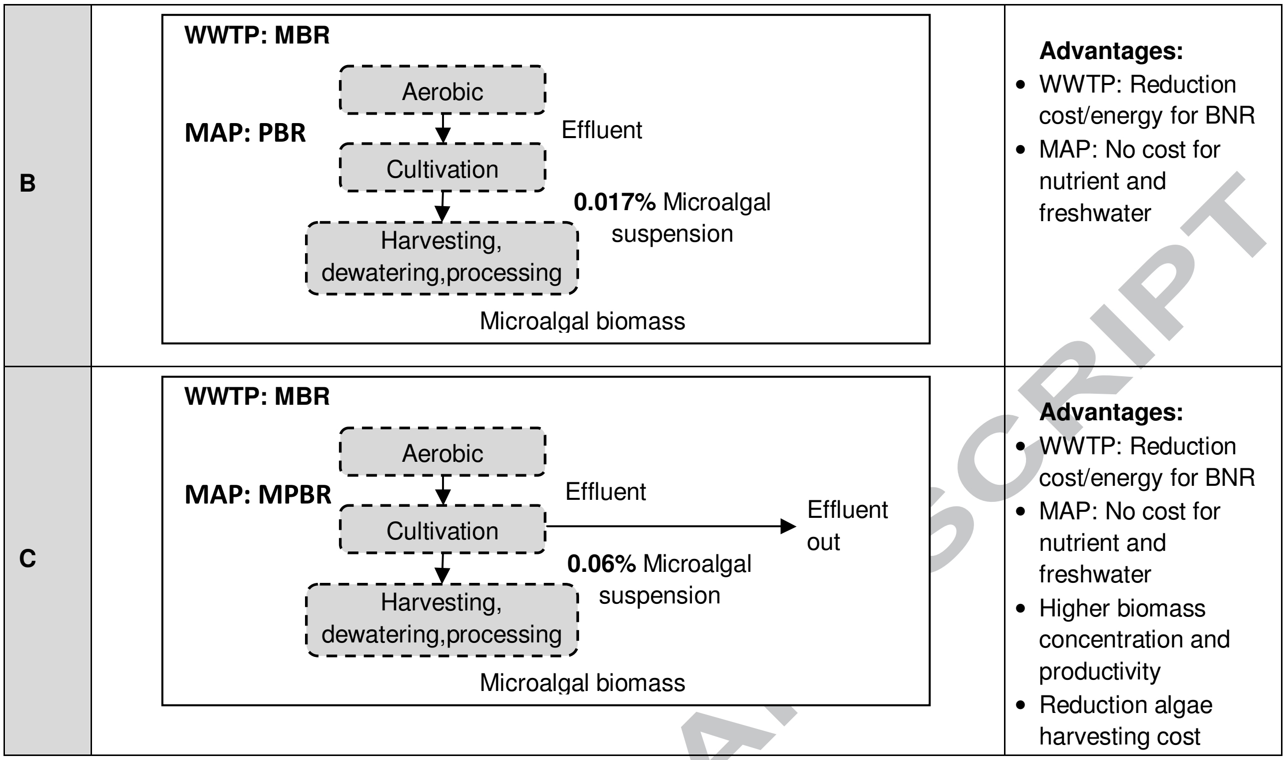


Figure 6 Comparison of different scenarios of (A) wastewater treatment plant (WWTP) using a standalone biological nutrient removal (BNR) and a conventional microalgal production (MAP), (B) combination of WWTP and MAP with conventional PBR, and (C) combination with MPBR. The MPBR shows its superiority by producing higher microalgal concentration (section 3.2)

Figure 6 shows three different scenarios of how a wastewater treatment plant (WWTP) and microalgae production (MAP) can be combined. Scenario A represents the baseline, which is the most unlikely scenario, where an MBR is operated by incorporating nutrient removal, while microalgae are separately cultivated in a PBR or in an open raceway pond. In this scenario, additional MBR investment and operational costs are required for civil construction (different reaction zones) and operational costs (circulation pump), respectively. For microalgae cultivation, more costs are required for freshwater, fertilizer, and additional cost of harvesting due to lower attainable biomass concentrations.

In scenario B, the additional construction and operational costs can be eliminated by polishing the MBR effluent with a normal PBR. The cost of freshwater and fertilizer can also be eliminated. According to Acién et al. (2012), the costs associated with fertilizer and fresh water supply can be up to 34.5% of material costs. The rest is for CO_2 supply, which can be avoided when using exhaust gas, which has been proven in many reports. One analysis of microalgae system and wastewater treatment plants integration, as done by Menger-Krug et al. (2012), also suggests that with optimistic assumptions, this integration may turn into net energy production.

In scenario C, all advantages of scenario B can be maintained. In addition, it has lower investment costs due to smaller volume and substantially (3 times) lower primary harvesting cost as a result of the higher biomass concentration obtained in the reactor. This corresponds to around 0.2-0.33kWh/m^3 of treated water or 0.02-0.033 €/m^3 treated water (the cost of 1 kWh is taken as 0.1 €) (Bilad et al., 2012).

4. CONCLUSIONS

This study reveals the potential of an MPBR to polish MBR effluents. The integration of microalgae cultivation (and pre-harvesting) in an MPBR with a WWTP offers a significant reduction in nutrient and primary harvesting costs in the microalgae processing, in addition to a cut in the nutrient removal costs in the WWTP. MPBRs allow the decoupling of biomass and medium by applying membranes enabling operation at higher D's, in comparison to the conventional PBRs which face microalgae wash-out problems at a very low D already. This directly results in higher biomass concentrations, higher productivities and also improved nutrient removal efficiency.

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Title:
Membrane photobioreactors for integrated microalgae cultivation and nutrient remediation of membrane bioreactors effluent

Research Highlight

- Integrated microalgae cultivation and nutrient removal in wastewater stream using MPBR
- MPBR effectively avoid wash-out and increase the optimum D of 0.2 day^{-1} in PBR to 0.5 day^{-1}
- 3.5x biomass concentrations and 2x volumetric productivities were achieved with MPBR
- Possible drawback: lower nutrient removal with increasing D